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THE EFFECTS ON STRUCTURES OF WINDS OF HURRICANE FORCE

by Herbert S. Saffir

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STRUCTURAL DIVISION

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THE EFFECTS ON STRUCTURES OF WINDS OF HURRICANE FORCE

by Herbert S. Saffir, Member, A. S. C. E.*

INTRODUCTION

On the average, one tropical storm of hurricane intensity will cross the Florida coast-line at some location each year. In view of this probability, and in the light of damage caused by past hurricanes, special consideration must be given to design for wind by structural engineers in this area. This paper will discuss some of the major structural effects experienced as a result of hurricane winds; shortcomings in our knowledge of wind pressure distribution on buildings will be mentioned briefly.

PAST HURRICANES IN THE MIAMI AREA

October 15-19, 1950 Hurricane:

Most recent hurricane to hit the Miami area was the storm of October 15th to 19th, 1950. It struck this area with a force almost as severe, although not of as long duration, as the great 1926 hurricane which caused such havoc. The highest wind speed measured by the U. S. Weather Bureau during this storm was 122 miles per hour, with estimated gusts of 150 miles per hour. Unofficial records indicated even higher velocities. (See Figure 7.)

Casualties and damage caused by this storm were not typical of the average storm of hurricane intensity crossing the Florida coast-line each year. However, as an indication of the potential damage these storms may contain, the following statistics covering the 1950 hurricane are given(1):

Hurricane of October 15-19, 1950
Casualty and Damage Summary for Florida

Deaths	4	Major damage:	
Major Injuries	16	Houses	580
Minor injuries	183	Trailers	188
Homes destroyed:		Minor or superficial damage:	
Houses	92	Houses	20,281
Trailers	156	Trailers	60
		Families suffering loss	28,954

Damage Estimates:

Property damage	$18,000,000
Crop damage	4,000,000
Power and communications	3,000,000
Highways, bridges, and city streets	250,000
Miscellaneous, includes trees, ornamental shrubbery, seawalls, a few small craft, and general cleanup	2,500,000
TOTAL FOR FLORIDA	27,750,000

*Asst. County Engineer, Dade County, Miami, Florida.

(1) U. S. Weather Bureau's Climatological Data, National Summary, Vol. 1, No. 13, 1950.

Purely structural failure during this storm was not as high as the statistics appear to indicate. Much of the damage was confined to roofs of residences and small structures. Tarpaper roofs were rolled up and blown off residences by the force of the storm. High negative pressures were indicated especially on flat roofed residences which suffered more damage than gable type structures. Some residential roofs had damaged framing and failure of roof anchorages. In some housing projects roofing materials littered entire blocks after the storm. (Figs. 9 and 10.)

A good deal of the roof damage was centered in veterans' housing projects, and criticism was directed at everyone concerned in the construction of these projects -- from building officials and government officials to developers, general contractors, and subcontractors. Although roof damage was severe in some veterans' housing projects, it is interesting to note that expensive apartments in the so-called "Gold Coast" section along the ocean also suffered considerable damage.

The over-all study of the effects of this storm on small residential structures indicated no gross negligence on the part of building inspectors, contractors or subcontractors. In most cases damaged residences appear to have been constructed in conformance with local codes and government specifications. Lack of attention to supposedly unimportant construction details was the reason for roofing failures in many cases. Details such as the type of roof nail head used, spacing of roof nails, insecure fastening of drip strips and flashing were some of the items not carefully considered, in many cases. On the whole, the possibilities of the existence of high negative pressures on roofs appear to have been ignored.

Structural steel radio towers in general suffered damage, and eleven in the Miami area were completely destroyed. Failure appeared to have been started by the buckling of individual members. No towers failed by overturning of the entire structure. Free-standing towers appear to have suffered more than guyed towers. Several guyed towers withstood the force of the hurricane without damage. (Figs. 11 and 12.)

Other than general roofing damage on smaller structures, and damage to radio towers, there was no very great structural damage in the 1950 storm.

A computation of wind pressures exerted by the storm of 1950 was made by the writer, based on the pressures which caused several freight cars to overturn. The average unit pressures on the face of these cars required to shift them into a condition of unstable equilibrium were 52.0 pounds per square foot.(2)

September 18, 1926 Hurricane:

The 1926 hurricane, which struck Miami on September 18, 1926, ranks as the worst storm in point of destruction ever to hit Florida. Property damage was estimated at over $100,000,000; over one hundred lives were lost in the City of Miami.

Out of approximately 30 high buildings in the Miami area, the Meyer-Kiser Building and the Realty Board Building were the only two materially affected structurally. Both of these buildings were of structural steel frame and were unusually narrow. The Meyer-Kiser Building was 17 stories high, 39 to 45 feet wide, and 140 feet long. Dimensions of the Realty Board Building were approximately the same, except for being two stories lower. The

(2) "Miami Suffers Slight Structural Damage in Severe 1950 Hurricane", E. A. Anderson and Herbert S. Saffir, CIVIL ENGINEERING, Vol. 20, December, 1950.

storm distorted the Meyer-Kiser Building so that the top of the structure was moved 24 inches out of plumb. (Figs. 13 and 14.)

Structural effects of the 1926 hurricane were reported by a Committee of the Structural Division, American Society of Civil Engineers[3]. No accurate determinations of wind pressures were made but the Committee made various estimates based upon structural distortions of the Meyer-Kiser Building. Referring to damage to a small observation room, about 18 by 21 feet in size, in which the walls were blown out and the four columns bent, the report states, "It would require a pressure of about 65 pounds per square foot to produce the distortion which occurred and this figure is probably as good as can be determined; but it cannot be taken too seriously because the area of exposure at the time of failure is uncertain." Evidence indicated during the 1926 hurricane that for areas of moderate size the storm probably exerted a pressure of more than 50 pounds per square foot, but there is no evidence that this was the case over the entire area of a building. The report states that there was no adequate wind-bracing in the Meyer-Kiser Building, and the bracing which was used was made valueless by the details. Clip angles were so thin that in bending they did not develop more than 25 percent of the value of the rivets. Connection details should have been designed for the same strength as that for which the main members were calculated.

It is interesting to note that none of the high reinforced concrete buildings in Miami showed a crack.

As in the recent 1950 hurricane, radio towers were destroyed. Five triangular free standing radio towers owned by the Tropical Radio Telegraph Company were blown down. Highest of these towers was 435 feet above the concrete pedestal. All towers failed by buckling of the steel[4].

Thousands of small homes were completely destroyed, some by being completely unroofed or having a whole story blown away. Reports indicate that rainfall was intense during the second part of the storm, and winds also carried salt spray, giving evidence that water impact played a part in the destruction[4]. Successions of wind gusts were felt as hammering effects on the high buildings. (Figs. 15, 16 and 17.)

September 15, 1945 Hurricane; September 17, 1947 Hurricane:

Other recent hurricanes which affected Miami were the September 15, 1945 storm, and the September 17, 1947 storm. The hurricane of 1945 caused damage upwards of $54,000,000. The several 1947 storms which struck the Florida coast caused damage estimated in excess of $100,000,000.

The hurricane which struck on September 15, 1945, made itself felt mainly in the destruction of the three giant blimp hangars at the Richmond Naval Air Base, about seven miles southwest of Coral Gables. Fire, fanned by the hurricane winds, destroyed the three hangars, and 25 blimps and 366 airplanes stored in the hangars. These hangars were of timber construction -- except for the concrete door frames and steel doors at the ends of the hangars -- and were built at a cost in excess of eight and one half million dollars in 1943. They were 1,058 feet long, 171 feet high, with a clear inside span of 237 feet, and were catenary arch-shaped structures each containing about 3,000,000 b. ft. of timber, of which 750,000 b. ft. were heavy timbers in the arches. The timber for the structures was pressure treated with a mixture of

(3) "Florida Hurricane, Final Report of the Committee of the Structural Division, Volume 95, Transactions of A.S.C.E., 1931".

(4) "The Florida Hurricane and Some of its Effects", F. E. Schmitt, Engineering News-Record, Volume 97, October 7, 1926.

ammonium and boron to make the wood as flameproof as possible. Two of the hangars were parallel and about 80 feet apart with east-west longitudinal axes. The third hangar was half a mile away, with its longitudinal axis north and south.

The structures were designed for negative pressures, with a wind load distribution based on small-scale wind tunnel tests made in connection with the design of the dirigible hangars at Akron, Ohio. Roofing and roof beams were torn away after the storm started, and after fires began in the huge hangars there was no way to remove the ships stored there or put out the fires in the hangars. Before the fire started, several of the blimps were reported to have been deflated by falling beams. These blimps, incidentally, were helium filled.

About eight miles to the south, the Homestead Army Air Base received considerable damage from the same storm. Timber buildings were severely damaged and in some cases timber roof truss anchorages in Army hangars at this base failed completely and trusses fell to the floor below.

October 5, 1948 Hurricane:

The hurricane which passed through this area on October 5, 1948, caused considerable small home damage in Broward County, 20 miles north of Miami. Tornadic winds were reported to have passed through one street of 15 homes, and left only 3 homes with walls standing after the wind had passed. A newspaper account of this occurrence states that "Witnesses told of one family which was sitting around the dining room table. The walls suddenly collapsed outward, the roof disappeared, chairs reared into the air, and possessions were whisked out into the dark."

The October 6, 1948 Miami Herald, in noting the effects of the storm on the Dade County Courthouse and its occupants in the jail in the top six floors stated, "They were safe and nothing could get in to harm them but County Jail prisoners high up in the Dade County skyscraper Courthouse were disturbed Tuesday night as the building swayed in the high winds. The Chief Deputy reported that some of the prisoners kept track of the swaying by watching the movement of water run into washbowls."

The courthouse structure stands 337 feet in height in a location unshielded on three sides, and is adapted to a study of wind loads, although the writer recommends a more quantitative test than the one the County prisoners used in the 1948 storm.

Chronologies of Past Hurricanes:

This paper is intended to cover observations and comments on tropical storms striking the Miami area only, in recent years. However, various chronologies of past hurricanes have been compiled, such as the chronological listing of cyclonic storms of the West Indies and North Atlantic Ocean from 1494 to 1944, in Ivan Tannehill's "Hurricanes"(5).

Tannehill states that a chronological table is valuable because it is reasonable to assume that all of the really great hurricanes which have been destructive to life and property on the islands of the West Indies and on the southern coasts of the United States have entered into the historical records of those regions.

From these lists we can safely draw conclusions as to the frequency, the time of year, and the destructive character, of tropical storms which have visited sections inhabited since the early years of the record.

(5) "Hurricanes, Their Nature and History", Ivan Tannehill, Princeton University Press, 1945.

As an indication that structural damage caused by hurricanes was prevalent before the 1926 Florida hurricane, Tannehill's reference to a storm of August 31, 1530, is quoted: "Principal place affected (by this storm) was Puerto Rico. This and the two preceding storms within six weeks blew down half the houses in San Juan; the remainder were unroofed. Great damage on the island; many cattle drowned."

The comparatively recent 1926 hurricane -- which damaged 80 percent of the structures in the Miami area -- can be called the starting point for actual studies of hurricanes and development of modern building codes in this area.

As an indication of the over-all damage and effects of hurricanes striking the entire United States coast since 1926, the following table is quoted from U. S. Weather Bureau statistics[1]:

Year	Total Number of Hurricanes and Tropical Disturbances	Number Reaching U. S. Coast	Loss of Life (Entire United States)	Damage (Entire United States)
1926	10	3	269	$106,500,000
1927	7	0	0	0
1928	6	3	1,836	25,000,000
1929	2	2	3	653,000
1930	2	1	0	Minor
1931	8	3	0	0
1932	11	5	0	0
1933	21	5	63	45,650,000
1934	11	4	17	4,760,000
1935	5	2	414	11,500,000
1936	17	6	9	2,300,000
1937	9	5	0	42,500
1938	8	4	600	300,245,000
1939	5	3	3	2,000
1940	8	2	51	4,743,550
1941	6	4	10	7,675,000
1942	8	2	8	27,101,000
1943	10	2	18	17,005,000
1944	10	4	62	163,010,000
1945	10	5	7	80,133,000
1946	6	4	0	7,200,000
1947	10	8	53	135,757,500
1948	10	5	3	18,400,000
1949	11	4	2	58,750,000
1950	12	4	19	35,850,000

(TABLE 2)

WIND VELOCITIES IN RECENT STORMS IN THE MIAMI AREA
(not from U. S. Weather Bureau Records)

The United States Weather Bureau has compiled excellent records on wind velocities and barometric pressures observed during recent hurricanes. The storm warning services instituted by the Weather Bureau have forecast and tracked hurricanes with great accuracy since the great 1926 storm; removing the uncertainty of their occurrence has enormously decreased property damage and loss of life. However, as an example of independently obtained

records, four anemometer charts and four barographs for storms of November 4, 1935, September 17, 1945, October 11, 1948, and October 17, 1950, are reproduced in this paper (Figures 1 to 8, inclusive). These readings were taken by the Florida Power and Light Company in the Ingraham Building in downtown Miami. The instruments are set at a height of approximately 230 feet above ground. From a study of the charts it is evident that velocities in some storms reached well over 150 miles per hour.

These charts are not necessarily intended to represent maximum velocities and minimum pressures occurring in these storms. For example, in the 1948 storm the center of the hurricane passed over the mainland north of Miami and the anemometer reading in downtown Miami does not represent the maximum wind velocities prevalent in the storm. Local variations, because of the effects of adjacent buildings, would of course affect the anemometer readings.

The writer feels that independent velocity data should be obtained whenever possible to supplement Weather Bureau material, since only two Weather Bureau stations exist in Miami[6]. As an extreme example, a volume on transmission tower design published in 1925 -- before the 1926 Florida Hurricane -- contains a table of maximum wind velocities recorded throughout the country at various points based on U. S. Weather Bureau data. The maximum wind velocity (for a period of five minutes) for Miami is 46 miles per hour.

The writer has also seen a wind velocity chart prepared in 1948 by a government agency, for structural design criteria covering the entire United States. Curves of extreme wind velocities have been plotted on a map of the continental United States. At Miami the extreme wind velocity is indicated as 90 miles per hour. Extreme velocities of more than 90 miles per hour can certainly be expected in Miami during hurricanes. Even if gust factors of 50 percent were applied to this chart, the design would be based on inaccurate data.

WIND LOADS USED IN DESIGN

Building codes in South Florida were greatly revised after the disastrous 1926 hurricane. Code requirements before 1926 called for only 20 pounds per square foot positive pressures. Unfortunately, our building codes in this area still do not cover negative pressures, internal pressures, shapes of buildings, etc., but confine themselves wholly to a listing of positive pressures.

The unified building code, in use in most of Dade County and Miami, states that for wind pressures the following standards apply:

Maximum Height Above Ground	Normal Wind Pressure Over Entire Height
25 feet	25 pounds per sq. ft.
75 feet	35 pounds per sq. ft.
over 75 feet	45 pounds per sq. ft.

The wind pressure upon sprinkler tanks, sky signs, or other similar exposed structures and their supports shall be taken as not less than

(6) Francis L. Castleman, Jr., in discussing wind forces on the Empire State Building, stated, "From a meteorological viewpoint three weather bureaus on Manhattan Island may be sufficient, but from the standpoint of the structural engineer, or rather the data that should be furnished to him by the meteorologist, this number would appear deficient."

fifty (50) pounds per square foot of the gross area of the plane surface, acting in any direction. In calculating the wind pressure on circular tanks, towers, or stacks this pressure shall be assumed to act on six tenths (6/10) of the projected area.

Negative pressures, of course, are of the utmost importance in considering the design of structures for wind loadings. Structural engineers in the area design for negative pressures and internal pressures, even though no specific mention is made of them in the building code. It is anticipated that our present codes will be revised to cover these points.

In some cases wind loads much in excess of those required by the code have been used on structures in this area. Loads of 60 and 70 pounds per square foot are now being used in radio tower design. A bridge recently completed in the Jacksonville area has used a design wind load of 75 pounds per square foot. These pressures established by designing engineers were based on the shape and location of the structure under consideration.

Our code recommendations do not safely reflect the negative loadings which occur during high winds and hurricanes. Careful attention in designing structures should be given to the actual pressure data for the structure under consideration.

As far back as 1895 wind-tunnel tests were made to indicate wind-pressure distribution on building models. (J. O. V. Irminger, in Copenhagen, 1895.) Wind tunnel tests by Hugh L. Dryden and George C. Hill were conducted for the National Bureau of Standards on wind distribution on mill-building models and a model of the Empire State Building (1931, 1933).

A recent series of wind-tunnel test results of great interest over a fairly wide range of building proportions was compiled in 1951 by the Iowa Institute of Hydraulic Research[7]. The tests were made in a three-dimensional wind tunnel on various gabled block structures, thin walls, hangar-type structures and simple building groups.

As a result of the data obtained in tests based on buildings of the simple block type, with gabled roofs of slopes varying from 0° to 45°, it is apparent that average negative pressures become extremely high. In a comparison of average pressures on middle and end sections of roofs, plotted as a function of the roof angle for various building proportions, test results obtained at the Iowa Institute of Hydraulics have been compared to A.S.C.E. recommendations given in the Fifth Progress Report, "Wind-Bracing in Steel Buildings", 1936. A.S.C.E. code recommendations for negative pressures appear far too low at the midsection of windward roofs and at the edge section of windward and leeward roofs. The Iowa report states that code recommendations do not safely reflect the negative loadings which may occur, and the report recommends a modification of existing codes (or a design based on actual pressure data for the structural geometry under consideration).

Pressures were plotted in this report in the dimensionless form as a ratio of $\frac{\Delta p}{\rho V_0^2/2}$ As an indication of high local uplifts, a peak value of -7.4 was determined for the maximum local negative pressure on the roof corner of a block-type model (roof angle 0°, quartering wind, length-width ratio of 4, height-width ratio of 3/2). Converting this dimensionless ratio to actual pressure for stagnation condition (+1) within the building, the maximum local

(7) "Wind-Tunnel Studies of Pressure Distribution on Elementary Building Forms" by Ning Chien, Yin Feng, Hung-Ju Wang and Tien-To Siao, Iowa Institute of Hydraulic Research, State University of Iowa, 1951.

uplift at the corner of the roof would be 78 pounds per square foot, for a velocity of 60 miles per hour, quartering wind. Changes in velocity, density and viscosity of the fluid medium (Reynolds Number changes) would not seriously affect the similitude between this particular model under wind-tunnel test and a full size prototype, since the model had sharp edges and corners.

Much other information is available covering wind-tunnel tests on various scale models of building structures. These give an indication of the wind pressures acting on special structures. The writer has cited the particular series of tests noted above because it appears to be the most comprehensive investigation available covering various building shapes under a wide range of conditions. However, very little is available concerning wind pressure data on full-scale buildings. Because of the frequency of hurricanes in this area, the writer suggests that Miami be used as a testing ground for obtaining full scale data.

CONCLUSION

The writer has indicated in this paper some of the structural effects of past hurricanes. A brief mention was made of various wind loadings specified in our building codes, and the shortcomings of these specifications. Other methods of obtaining data for wind pressures on structures are mentioned. In view of the trend toward buildings with lower dead to live load ratios occasioned by the use of prestressed concrete and light metals, the writer believes that further study is needed to increase our knowledge of proper wind loads and wind-pressure distribution. The designing engineer in this area -- and in many other areas faced with the occurrence of hurricanes or typhoons -- is continually confronted with the problem of balancing safety and economy in building design.

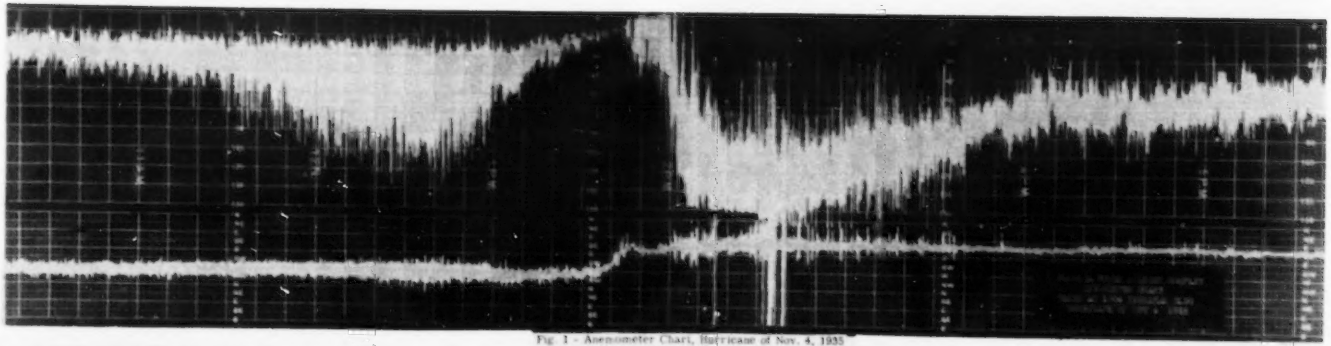

Fig. 1 - Anemometer Chart, Hurricane of Nov. 4, 1935
Ingraham Building, Miami, Florida

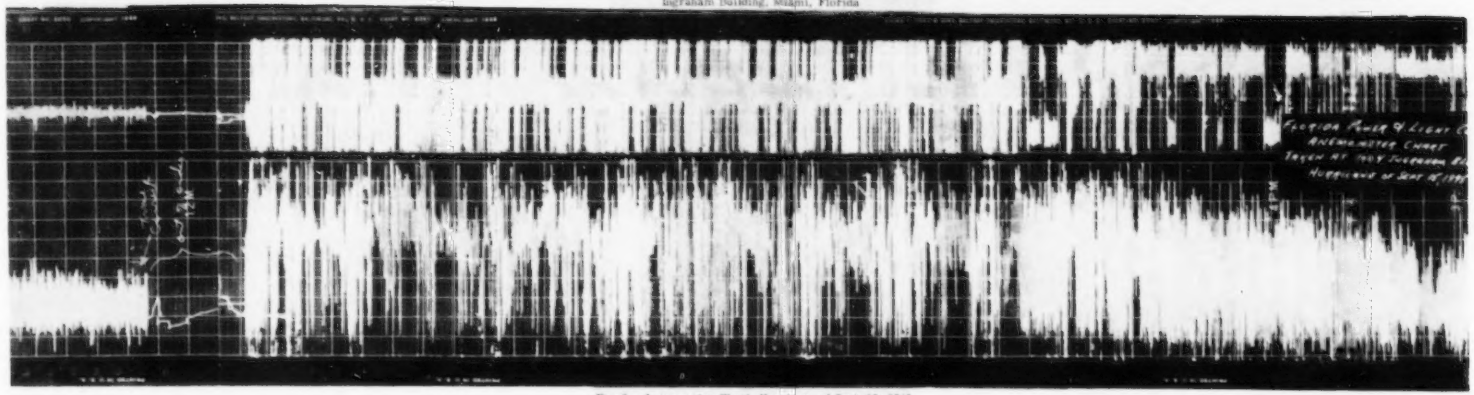

Fig. 3 - Anemometer Chart, Hurricane of Sept. 15, 1945
Ingraham Building, Miami, Florida

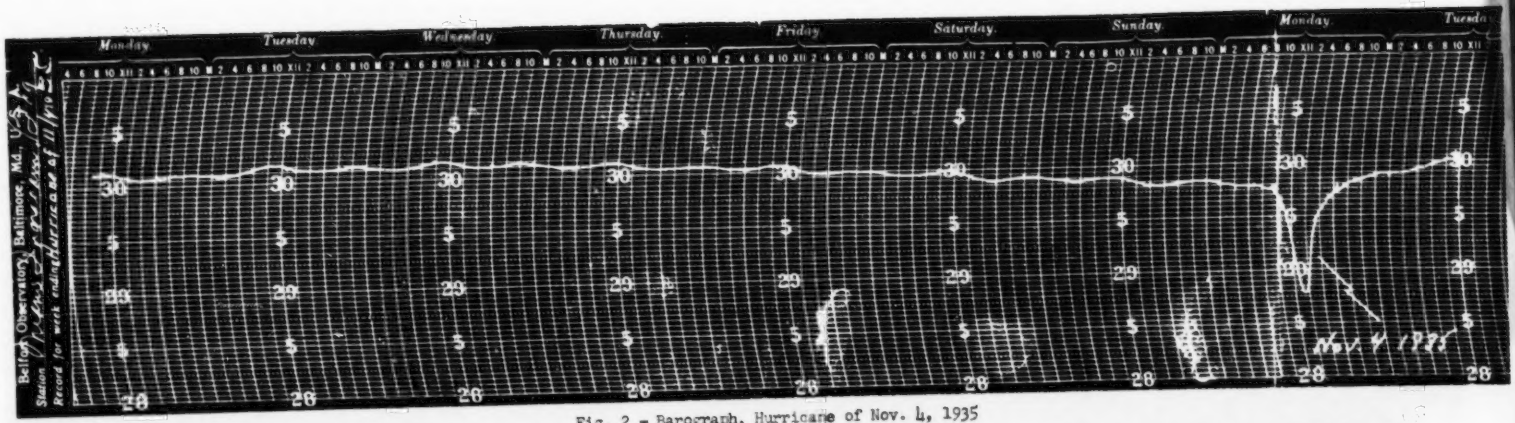

Fig. 2 - Barograph, Hurricane of Nov. 4, 1935
Ingraham Building, Miami, Florida

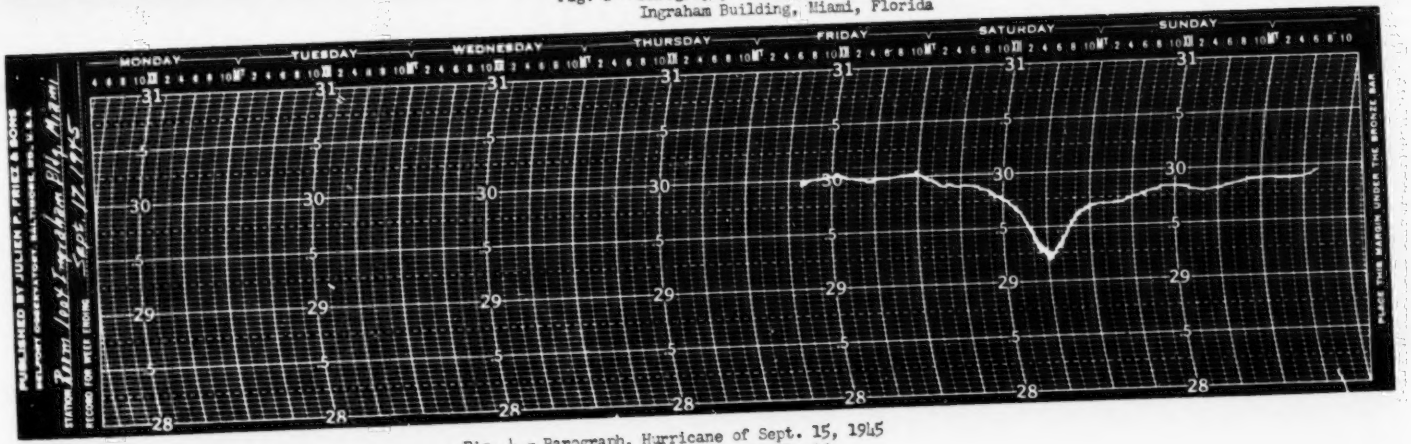

Fig. 4 - Barograph, Hurricane of Sept. 15, 1945
Ingraham Building, Miami, Florida

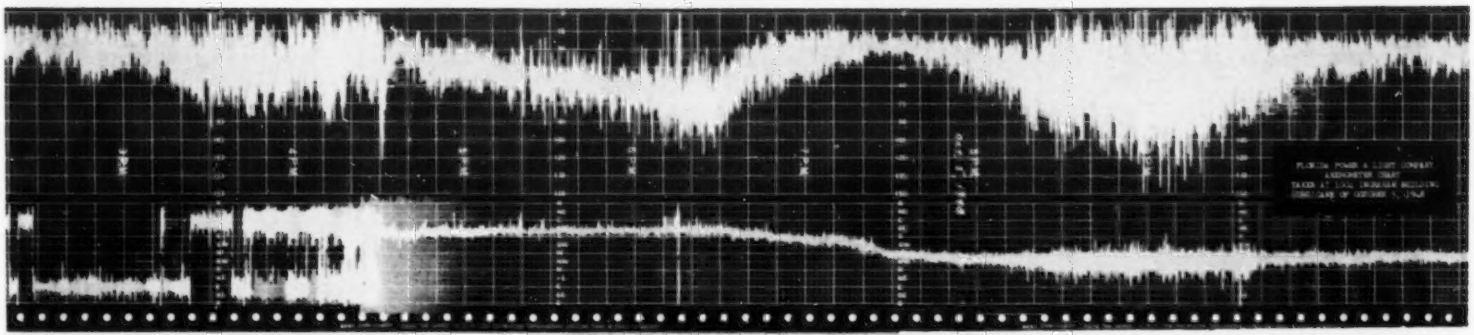

Fig. 5 - Anemometer Chart, Hurricane of October 5, 1948
Ingraham Building, Miami, Florida

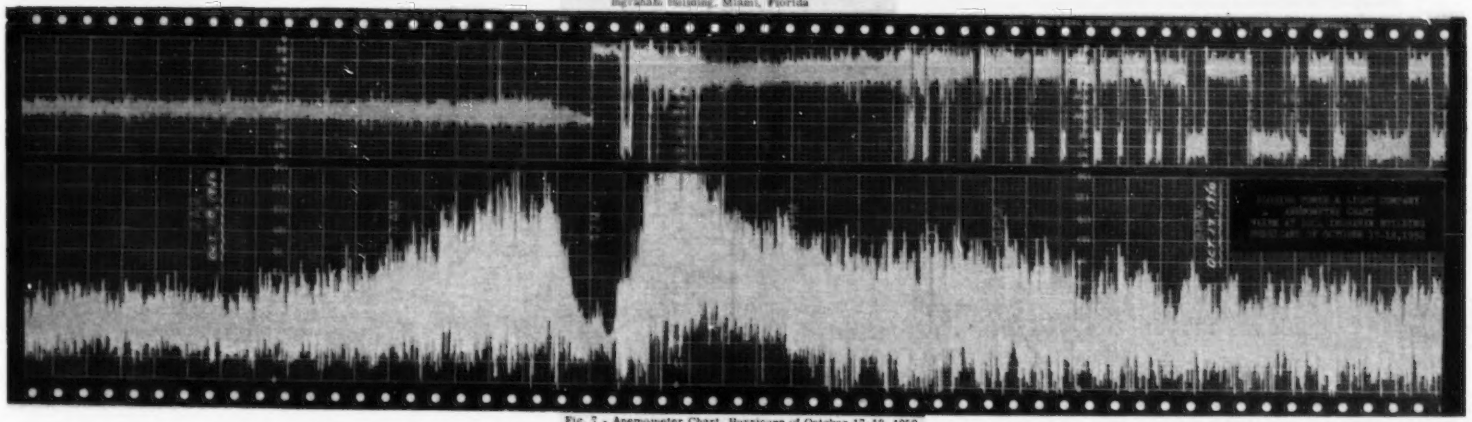

Fig. 7 - Anemometer Chart, Hurricane of October 17-18, 1950
Ingraham Building, Miami, Florida

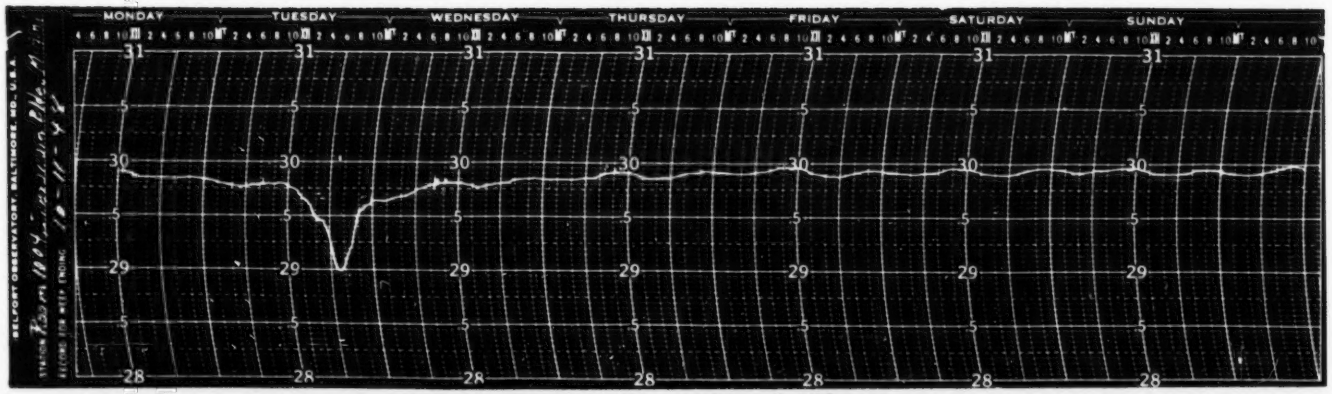

Fig. 6 - Barograph, Hurricane of Oct. 5, 1948
Ingraham Building, Miami, Florida

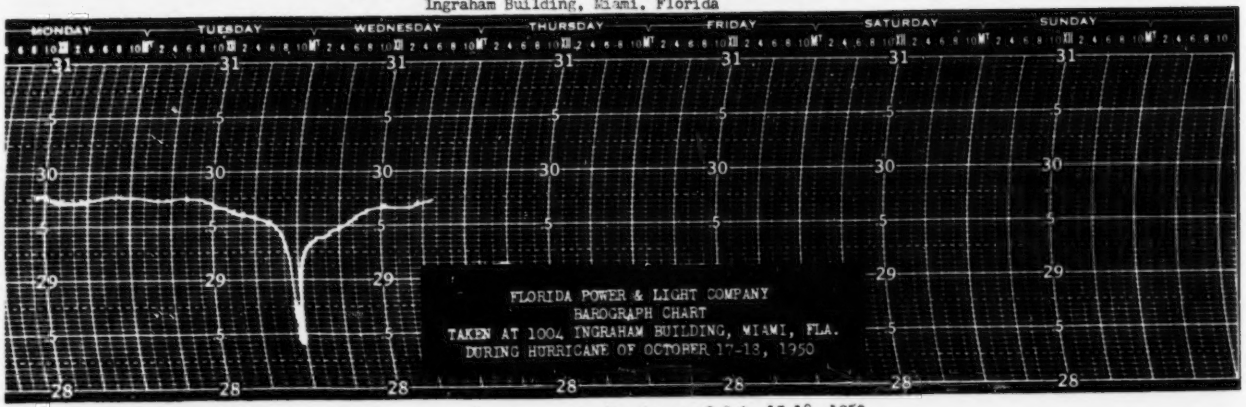

Fig. 8 - Barograph, Hurricane of Oct. 17-18, 1950
Ingraham Building, Miami, Florida

Fig. 9 - October 1950 Hurricane. Exterior damage to newly constructed project home; some structural damage.

Fig. 10 - October 1950 Hurricane. Typical view of roofing damage in recently constructed

Fig. 11 - October 1950 Hurricane, Radio Station WIAM, one of two radio towers both destroyed by this storm.

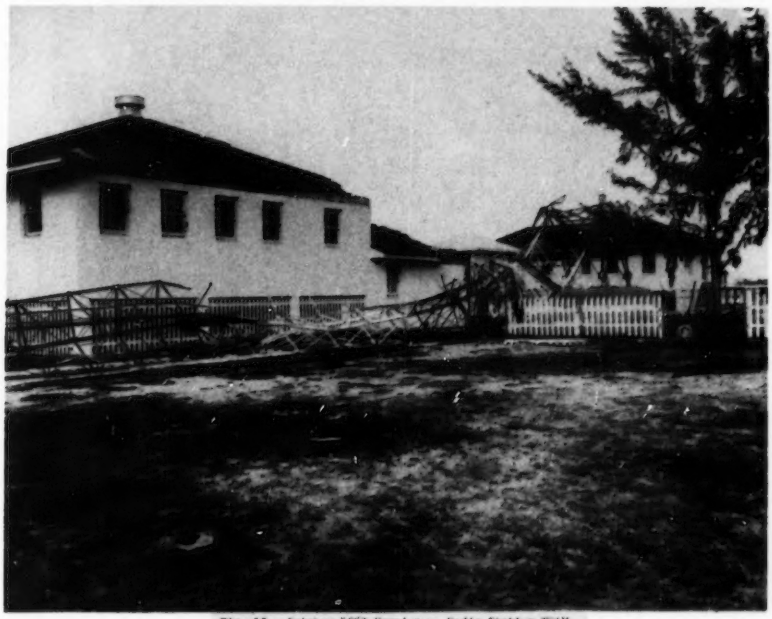

Fig. 12 - October 1950 Hurricane, Radio Station WIAM, one of two radio towers both destroyed by this storm.

Fig. 13 - September 1926 Hurricane, Meyer-Kiser Bldg. after 1926 hurricane. Note missing walls in lower portion of building.

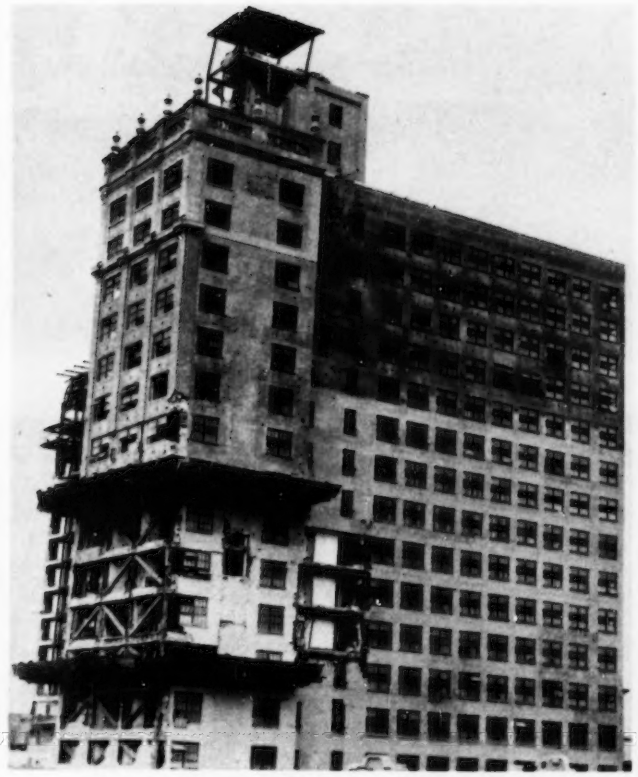

Fig. 14 - September 1926 Hurricane, Meyer-Kiser Bldg. after 1926 hurricane. Note distortion of penthouse on top of building.

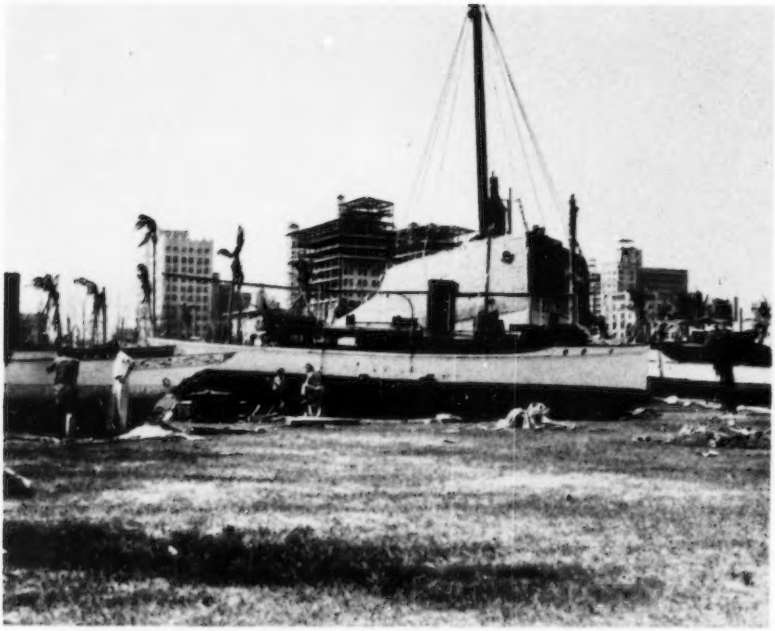

Fig. 15 - September 1926 Hurricane, view of downtown area near Biscayne Blvd. after storm.

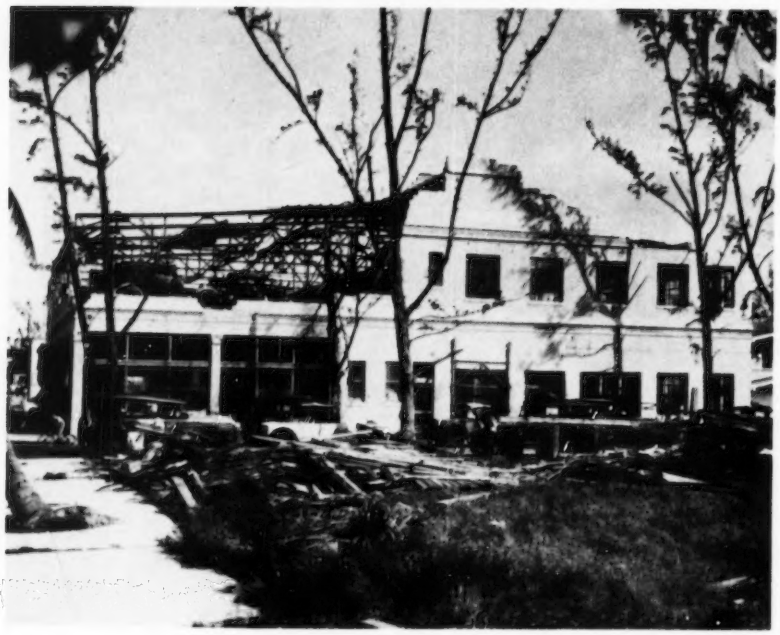

Fig. 16 - September 1926 Hurricane, damage to garage roof.

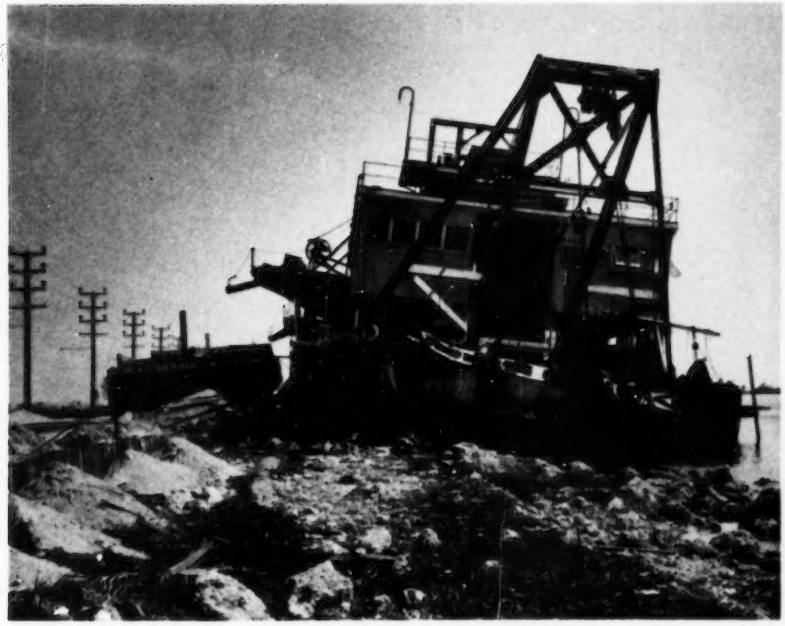

Fig. 17 - September 1926 Hurricane, view showing dredge blown up on County (MacArthur) Causeway after storm.

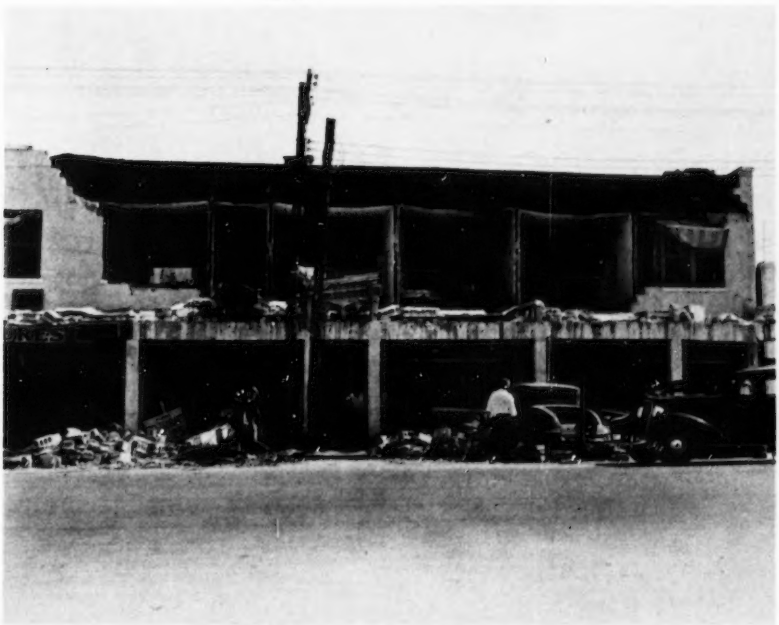

Fig. 18 - October-November 1935 Hurricane, view of building on Bayshore Drive between N.E. 13th and N.E. 14th Streets after storm.

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